68th International Astronautical Congress (IAC), Adelaide, Australia, 25-29 September 2017.

Technology Development and Design of an Electrically Driven Pump Fed (EDPF) Bi-Propellant Propulsion System for a Mars Ascent Vehicle (MAV)

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Abstract

A Mars Ascent Vehicle (MAV), as part of a potential Mars Sample Return (MSR) campaign, is a very unique challenge and has been the focus of technology development and design efforts at JPL for the several decades. Recent trajectory studies, for the current range of notional MAV payloads (6-25kg), evaluated performance using propulsion systems in the 2.5kN to 4.5kN (600-1000lbf) thrust range. The study examined several propulsion system approaches—solid rocket, bi-propellant and hybrid propulsion systems—and developed a ranking based on several key figures of merit. This paper focuses on the evaluations conducted for the two bi-propellant propulsion system options considered for a potential MAV. Historically, bi-propellant propulsion systems have been considered for this application; this study took a fresh look at both a conventional State of the Art (SOA) pressure fed bi-propellant propulsion system and recent developments using small EDPF bi-propellant propulsion systems.

1. Introduction

The most recent notional Mars Sample Return (MSR) mission architecture [1] is designed to return soil/rock/gas samples collected on the Martian surface back to Earth. MSR could consist of a combination of three separate missions. The first mission would cache samples for retrieval. NASA's Mars 2020 rover is planning to collect samples that could be returned in the future. The second mission would provide an orbiter carrying a Earth return vehicle. The third mission would provide a sample collection rover. In one option, an MSL-class would transport and erect the conceptual MAV. The samples collected by the rover would be loaded into the forward payload area of the potential MAV, which would then be erected into a vertical position for launch. The conceptual MAV would then be launched to transport the science samples from the Martian surface to a low circular orbit for rendezvous with the orbiting Earth return vehicle. One of the key components for MSR is the MAV. An in-depth study was initiated in 2014 and concluded in September 2015 that evaluated several potential propulsion MAV options. In the current MSR concept, the potential MAV is a small (~250 kg) vehicle capable of being launched from the surface of Mars and obtaining a near-circular orbit of approximately 300 km. The payload is contained in a volume at the nose of the vehicle. This is called the orbiting sample (OS) container.

Several bi-propellant studies on a conceptual MAV have previously been performed. A two-stage bi-propellant study was performed in the late 1990's [2] and a follow-on study was performed in the early 2000 timeframe [3]. This most recent study [1], examined single stage to orbit (SSTO) and two stage to orbit (TSTO) propulsion systems to lift a range of payload (OS) from 6.5kg to 25 kg. [1] details the various propulsion configurations evaluated during the study and the qualitative and quantitative figures of merit (FOM) used to evaluate the different options. Green shaded areas are considered a positive attribute; a yellow shaded area is considered neutral and light brown shaded area is considered negative. The numerical scores associated with this study are shown in Figure 1. Table 1 details the 7 configuration shown in [1]. The results show that the Hybrid SSTO propulsion option (case#7) has the overall highest system ranking. Primarily this was a result of the hybrid fuel being able to survive temperatures in the -90 deg. C range. This is far lower than other propellant options. The main assumption for power while on the surface of Mars was that there was no RTG available. As such this feature of the hybrid fuel differentiates it from other propulsion options such as storable bi-propellant and solid propellant systems. A close second to hybrids in this study is the electrically driven pump fed (EDPF) SSTO bi-propellant propulsion system (case#5). This is then followed in third place by the conventional pressure fed SSTO propulsion system (case#6). The details of the study and the complete list of assumptions and systems evaluated are contained in reference 1. Details of the Hybrid SSTO propulsion system of case #7 are also presented in [1] and [4]. The EDPF bipropellant option and the conventional bi-propellant systems are the focus of this paper and will be detailed further. As will be seen the EDPF bipropellant option offers some distinct benefits for configurations that require

		Case 1a.3	Case 1b.3	Case 2a.3	Case 2b.3	Case 5.3	Case 6.3	Case 7.3
FOM	**weight**	1	2	3	4	5	6	7
Total **system** mass	15	7.08	6.18	8.13	7.20	8.47	7.76	8.55
System Power	15	8.44	7.56	8.97	7.88	6.98	5.83	7.51
Sample Environments	10	7.93	8.04	7.25	7.42	8.86	8.98	6.23
MAV max dim.	10	9.40	8.98	9.57	9.09	8.65	8.42	9.08
Flexibility	15	0.57	0.00	1.66	2.79	9.54	8.54	10.20
MAV System Cost	8	6.00	6.00	5.00	5.00	8.00	7.00	10.00
MAV Test and Verification	8	5.00	5.00	4.00	4.00	10.00	8.00	7.00
MAV Comp. TRL	7	8.00	8.00	7.00	7.00	8.00	10.00	6.00
MAV complexity	12	6.00	6.00	5.00	5.00	6.00	7.00	10.00
Total Weighted Score		**631**	**592**	**631**	**614**	**822**	**780**	**845**

Figure 1. Numerical ranking of study concepts

minimum system volume while maximizing propulsion system performance. From a technology standpoint, Figure 2 highlights the current State Of the Art (SOA). Pressure fed have matured and have reached a plateau. The ability for additional performance is limited. There are only two different pathways to increase performance. These are to use more energetic fuels or to use pumps. Energetic propellants have been evaluated at JPL, [5] shows the most recent results. Although increase performance can certainly be achieved the various liquid oxidizers and fuels have handling, storage and compatibility issues associated with them. Although not a complete dead end the commercial adoption of these systems has not warranted the increased effort to solve or avoid the array of safety issues that come with these energetic compounds. Air Force Research Laboratory (AFRL) is currently re-looking at some propellant combinations coupled with advanced material research that has occurred in the last 20 years. The following discussions will focus on the pump fed options that use SOA conventional storable bi-propellant combinations.

2. BI-PROPELLANT BENEFIT AND TECHNOLOGY DESCRIPTION

Storable bi-propellant rocket propulsion has been a mainstay for over 60 years for a variety of in-space spacecraft applications. Most of the spacecraft systems to date have used pressure-fed systems. Common propellants used are Monomethyl Hydrazine (MMH) and Nitrogen Tetroxide (NTO) for the main engine propulsion system. Typical spacecraft main engine size has remained less than 890N (200 lbf). This has been driven primarily by requirements to satisfy commercial spacecraft needs. Larger engines had been developed; for example, the Apollo program in the 1960's developed the lunar lander engine [reference 4 and 5] (40kN for descent engine and 16kN for ascent engine). But with no subsequent commercial requirement or application for this class of engine, there has been very little impetus to develop engines in the 2.5kN to 25 kN class. The few that have been produced over the years have were usually pressure-fed engines with fairly large expansion ratios to increase performance. Only one pump-fed engine of any note was developed, XLR132 [6]. This engine was a turbine-driven pump system and is difficult to compare to battery driven systems described in this paper. Larger thrust engines >>25kN have been developed for launch vehicles. Again these are turbine driven pumps and have very limited applicability for near term in-space applications.

Figure 3 shows a historical perspective summary for pressure-fed monopropellants and bi-propellant propulsion systems, and the expected benefit for using pump-fed technology. These systems have been primarily used for descent missions.

A more detailed breakdown of pressure-fed and pump-fed storable bi-propellant systems will be described in the next two sections.

2.1 Conventional Bi-propellant MAV description

A conventional pressure-fed bi-propellant system offers a reliable but fairly complex configuration compared to monopropellant, solid, and hybrid propulsion systems. The complexity is driven purely by the number of components required. Various valves, filters, regulators and other components do not pose a technology challenge. The Technology Readiness Level (TRL) of the individual components are typically high (TRL>6). This is a direct result of pressure-fed systems being the current SOA. They have been as used on a number of robotic missions over the past several decades. Missions such as Cassini and Juno are good examples of recent outer planet missions using storable propellant with a pressure-fed propulsion system. Multiple commercial spacecraft for geosynchronous operation have also used pressure-fed bi-propellant propulsion systems for orbit transfer from low-Earth orbit (LEO) to geosynchronous orbit (GEO). For this MAV study, due to the need for the vehicle to remain on the surface of Mars for durations potentially in excess of 2 years, several options to reduce and minimize power were examined. From a propulsion viewpoint using low temperature propellants is an option worth exploring. For this MAV study, it was decided to use the following propellant combination: MON30 and MMH. MON30 is NTO with 30% nitrous oxide (NO). This reduces the freezing point to -82 deg. C. MON30 has not been utilized recently although the military had evaluated and tested systems successfully during the 1950 and 1960's. Although there were no significant issues encountered with engine testing using this propellant combination, the military or commercial need for low-temperature propellants was not a strong discriminator for terrestrial and near-Earth spacecraft applications. As a consequence, further development and use of this fuel was not pursued.

Another key benefit for storable bi-propellants is their hypergolic nature. A propulsion system with no requirement for an ignition system has a significant benefit since the mass, power and complexity needs of an ignition system can be a significant driver for small propulsion systems such as those considered for the MAV. Other propellant combinations, hybrids, solids, non-hypergolic bi-propellants and cryogenic options have to include ignition systems with the associated mass, power and complexity that is incurred.

In terms of optimization of pressure-fed bi-propellant propulsion systems, this has occurred over the last 50 years. For spacecraft this optimization has resulted in chamber pressure around 1.723 MN/m2 (250 psi). for a typical thrust of around 445N (100 lbf). As a result, propellant tank pressures have been established in the 2.757 MN/m2 (400 psi) range with around 1.034 kN/m2 (150 psia) across the injector and feed system. As can be seen in figure 4 for MMH and MON3, the theoretical performance is a strong function of mixture ratio. A mixture ratio of 1.65 is commonly used. This results in almost identical volume propellant tanks. Additional factors include the need to balance combustion temperature, performance, and chamber wall life.

A notional layout of a pressure-fed bipropellant propulsion system for the MAV study is shown in Figure 5. As mentioned previously, the performance was based on MON30, a low temperature variant of NTO. This was selected to try and minimize the system power to keep the MAV above the propellant freezing point during the majority of the stay on the surface of Mars. The proposed layout controls propellant tank pressure using a gaseous nitrogen pressurization system feeding two propellant tanks. Two gas regulators are used to reduce the nitrogen pressure. The first regulator controls nitrogen pressure to 8.618 MN/m2 (1250 psi) for RCS use and then the second regulator controls the pressure from 8.61 MN/m2 (1250 psi)down to around 2.757 MN/m2 (400 psi) for main propellant tank operation. To meet the pressure needs of this system, the nitrogen supply tank pressure was established at 68.9 MN/m2 (10,000 psi). The nitrogen pressure is isolated using a conventional pyrotechnic valve throughout most of the mission. The pyrotechnic valve is actuated prior to launch from the surface of Mars. After this valve is actuated it then ruptures the downstream burst disks that feed each propellant tank. The propellants are consequently isolated from the rest of the system prior to the rupture of the burst disks. Other options are available but the passive nature of a burst disk compared to a pyro actuated valve coupled with its minimum mass makes this an attractive option. One of the main reasons for this system of isolation outlined above is to avoid any vapor migration issues that may occur during a long mission and surface stay. Other options like check valves or other permeable devices could be considered but issues with FORP (Fuel Oxidizer Residual Products) that ma occur in long-duration missions can be avoided with this approach.

For all the potential MAV propulsion systems evaluated [3], solids, bi-propellant and hybrids, a Reaction Control System (RCS) would be required. The RCS needs to meet the requirement for three axis stabilization and control throughout the trajectory from the surface of Mars to Low Mars Orbit. For the pressure-fed bi-propellant case, the minimum mass option selected was a cold gas system using gaseous nitrogen. Figure 5 shows the conceptual propulsion system. It uses the main nitrogen tank gas regulated to 1250 psi. It is isolated from the gas thrusters by the pyrotechnic valve between the supply tank and the first regulator. The RCS system consists of four 22N and four 5N thrusters. The Guidance Navigation and Control (GN&C) subsystem provided the initial RCS requirement based on 3 degrees of freedom (DOF) analysis. Recent 6 degree of freedom evaluations indicate that the thrust and number of thrusters may be reduced to a slightly lighter system mass consisting of six 10N thrusters.

2.2 MAV THRUST

The thrust for MAV has been an iterative process between GN&C and propulsion. The current study used 3560N as the last iteration on thrust. This is much higher than typical SOA pressure-fed bi-propellant thrusters. Both bi-propellant propulsion systems evaluated would require the development of a new thruster. This development is not anticipated to be a significant challenge. Higher thrust bi-propellant chambers have been developed and the risk for this new development was considered low.

The following discussion details the thrust for the MAV. As will be seen the pump fed bi-propellant thruster offers key benefits for the MAV configuration that are prohibitive for the conventional pressure fed system.

The thrust of a generic rocket propulsion system is given by equation 1, where T is thrust (N), m_e is mass flow (kg/sec), V_e is gas velocity (m/sec) at the nozzle exit plane, Ae is nozzle exit plane area (m^2) Pe is exit pressure (N/m^2) and P_0 is external pressure (N/m^2).

$$T = m_e V_e + (P_e - P_0) A_e \qquad (1)$$

Examination of this equation shows specifically the methods by which the thrust can be increased. For either bi-propellant propulsion system the following approaches can be employed. The most obvious would be to operate where P_0 is zero. Since this is the environmental pressure there is very little that can be done physically to change the value on Mars. Martian atmosphere is less than 10 mbar. Landing at higher altitudes lowers the ambient pressure but changes in ambient pressure of this magnitude have very minimal effect on the ability to generate higher thrust. The next approach is to increase mass flow (me). This is probably the most commonly used approach. For a conventional pressure fed bi-propellant system this is achieved by an increase in propellant tank pressure (Pt) to increase the propellant flow. The increase in propellant tank pressure however results in a propellant tank (dmpt) and pressurization gas tank (dm_{pgt}) mass increase as shown in equation 2.

$$dP \times dm_{increase}/dP_{tank} = dm_{pt} + dm_{pgt} \qquad (2)$$

There are also secondary mass increases from vehicle structural changes due to these tank increases resulting from an increase in the propulsion tank pressures. These were included in the study but are second order effects compared to the propulsion system mass increase ($dm_{increase}$). This increase in system mass are only accommodated if the payload mass can be decreased by the same mass. Otherwise the propellant mass has to increase which results in a system mass growth.

Another common approach to increase thrust in equation 1 is to increase the nozzle exit area and hence velocity at the exit of the nozzle, V_e. This is commonly achieved by increasing the nozzle length and area ratio. This results in a nozzle mass increase due to the increased conical length but for reasonable area increases can provide 1-2 % increase in Isp after taking into account the nozzle dry mass increase. The MAV has some configuration constraints that are dictated by the available space within an aeroshell delivery system for Mars. Several configuration trades have been made. The results of these configuration trades have concluded that there is a fixed length to diameter ratio (L/D) that the MAV has to stay within. The current L/D is around 5:1. For the pressure fed propulsion system attempts to increase the area ratio are very. The EDPF bi-propellant propulsion system however has two distinct approaches that result from this architecture that allow area ratio to be incorporated. First the helium tank volume requirement is less than the pressure fed architecture due to the lower propellant tank pressure required. The second is that the chamber pressure can be increased by changing the pump operating conditions. The resulting higher chamber pressure with a fixed thrust requirement implies the throat diameter can be reduced. This coupled with the reduction in length of the vehicle allows the area ratio to be increased.

2.3 EDPF BI-PROPELLANT MAV DESCRIPTION

An EDPF bi-propellant propulsion system has not been previously used in space. For large thrust systems associated with launch vehicles, pumps have been a common solution since the early vehicle designs. The drive mechanism for these pumps are typically turbines (turbo-pumps) due to the large power demands of these high flow, high thrust systems. Scaling of large turbo-pumps down to the 2.0kN to 25kN thrust range has proved problematic and costly. Recent developments in lithium-based battery technology coupled with high power density electric motors and the use of additive manufacturing of high speed rotating components has provided an opportunity to apply electrically driven pumps to this thrust class. An EDPF system offers a distinct advantage in that, unlike the conventional pressure fed bi-propellant propulsion system, the propellant tank mass (mpt), pressurization tank (mpgt) and pressurant gas (mpg) mass are constant and independent of combustion chamber inlet pressure. The mass increase for increased chamber pressure is simply the pump mass increase (dm_p) and battery mass increase (dm_{bat}) as shown in equation 3.

$$m_{increase} = dm_p + dm_{bat} \tag{3}$$

A thrust level for the EDPF bi-propellant propulsion system was set at 3560N and employed an area ratio of 40:1. The optimization of thrust and nozzle area ratio was not performed for this study. One of the benefit of the EDPF propulsion system is that the chamber pressure can be traded against specific impulse, Isp, by increasing the engine chamber pressure and increasing the area ratio. The values used for the study were to maintain a similar set of requirements across the various configurations being evaluated.

The layout of the EDPF propulsion system used for this study is shown in Figure 6. The pump is located at the engine inlet upstream of the engine inlet valves. An assumption was made for this study that both propellants, Mon30 and MMH would be driven from a single electric motor. This approach is expected to minimize pump mass. This assumption will be further investigated to ensure that safe operating conditions can be maintained throughout the operational life. The feed system is a regulated system somewhat like the conventional pressure fed system described in 2.1. The key difference is the use of pyrotechnic valves for isolation of the two propellant tanks. It was an opinion that burst disks although a potential solution may require some development for low pressure operation. The RCS is the same for both architectures. This is currently envisaged as a 1250 psi gaseous nitrogen system. The propellant tanks are operated and regulated at 50 psi. This pressure is below the minimum wall thickness threshold for a metallic propellant tank and so no mass savings are realized from the lower pressure. The mass savings is from the reduced gas mass required and the associated volume of the pressurant tank.

3. RECENT EDPF TECHNOLOGY DEVELOPMENTS

Ventions LLC. first began work on small-scale electric pump technology for rocket engine propulsion during 2009 under a NASA JPL funded program to evaluate use of pump-fed liquid bipropellant engines for the MARS Ascent Vehicle. As part of this effort, Ventions utilized a novel fabrication methodology to realize high-speed impellers approximately 1-inch in diameter with exit blade heights as small as 0.025-inches. The program resulted in successful demonstration of a first-of-its-kind electric motor-driven centrifugal pump operating at 50,000RPM, and led to further optimization of successive generations for flight-like packaging in a compact, highly integrated form-factor, Figures 7 & 8.

Most recently, Ventions successfully designed, fabricated and flight tested a 300lbf, electric pump-fed LOX / IPA engine in a 9-inch diameter sounding rocket under the DARPA ALASA (Airborne Launch Assist Space Access) Phase I Program. Similar pumps are also currently being used by Ventions in the DARPA SALVO (Small Air Launch Vehicle to Orbit) stage to pressurize two 1,000lbf LOX / RP-1 regeneratively cooled engines, and in a scaled-up version for a 4,000lbf LOX / RP-1 engine for NASA KSC launch vehicle applications. Ventions has recently been acquired by Moog LLC and is now part of their technical capability

4. RESULTS

The configuration and key parameters from the study for two notional bi-propellant MAV configurations are shown in figures 9, conventional pressure fed, and 10, the EDPF option. Detailed mass breakdowns for both configurations are shown in table 2. The pump configuration also provides just over a 5% decrease in overall length. This is driven primarily by the size of the nitrogen tank. A 40:1 nozzle was assumed constant for both configurations. The additional length may be traded for increased performance in the EDPF configuration. This will be a trade for a future study. The gross liftoff mass (GLOM) for the EDPF configuration is just over 4 kg larger than the conventional pressure-fed bi-propellant propulsion system. This is primarily due to pressurant tank requirements. The lower propellant tank pressure requirements result in a significant volume reduction for the amount of pressurant gas. This smaller volume results in a mass decrease and more importantly a decrease in the vehicle length, around 5%.

5.Discussion

The main issue associated with the EDPF bi-propellant propulsion system is its lower Technology Readiness Level (TRL) compared to the conventional pressure fed bi-propellant propulsion system. Currently funding for this type of system development is not envisaged. The EDPF bi-propellant propulsion system has two other key challenges. The first is the battery operating parameters and the second is the use of a single shaft for the two propellant pumps.

The pump electrical power is currently supplied from two battery packs. Each battery pack consists of 12 lithium polymer cells. Each pack is capable of providing 125 Amps. The expected current requirement is 111 amps/pack. Pump efficiency is a key factor in the power required. The current study assumed an efficiency of only 43% that was obtained during initial testing. Recent pump testing with slightly modified impeller geometry has shown that this can be increased to 65%. With this sort of efficiency, decreases in electrical power and hence battery mass required can be realized. Ventions LLC has conducted numerous ground tests using EDPF propulsion systems and the battery power and current discharge have not been an issue during any of these test campaigns. The open challenge however is to evaluate the battery current discharge under all conditions and ensure that spacecraft design principles that are currently in place for spacecraft battery systems do not prohibitively influence their use or result in excessive mass increase to provide very high margins of safety.

The other challenge is the single shaft configuration for the EDPF system. This is expected to result in a minimum mass for the pump. Having the fuel and oxidizer in close proximity raises a safety concern due to the possibility of seal leakage resulting in hypergolic ignition. The short exposure time prior to launch and the short MAV trajectory duration reduces the time during which any leakage and hypergolic ignition can occur. It however does not eliminate the possibility. Several design options can be implemented to try and prevent potential leakage and potential ignition such as an inert barrier purge or redundant seals. To reduce the risk completely separate fuel and oxidizer pumps could be considered. This will increase the system mass. An evaluation of options to reduce this risk is expected to be performed in subsequent studies.

6. CONCLUSIONS

An extensive study was performed by the JPL Propulsion Group during FY15 and FY16 that evaluated several configurations for a MAV architecture. Although the evaluation resulted in the selection of a hybrid propulsion system as the baseline for further technology development, storable bi-propellant configurations that were also highly valued offered solutions that were only slightly behind the leading candidate.

Two bi-propellant options for a potential MAV were evaluated, conventional pressure fed and the lower TRL EDPF propulsion system. The results from the study indicated that the EDPF propulsion system offers a distinct decrease in GLOM and reduced overall length when compared to the conventional pressure-fed configuration. In both cases, a new bi-propellant thruster development would be required. This is not considered a significant technology effort. The pump development and battery for the EDPF system would require technology investment to make these a reality.

ACKNOWLEDGMENTS

The technology study was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors would like to thank the Jet Propulsion Laboratory for funding this study through its Mars Technology Development Program.

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Configuration #	Description
1	Solid propellant , 2 stage with guided 1st and 2nd stage
2	Solis propellant, 2 stage with guided 1st and 2nd stage
3	Solid propellant with guided 1st stage and unguided 2nd stage
4	Solid propellant with guided 1st stage and unguided 2nd stage
5	Pump fed bi-propellant using Mon25 and MMH
6	Pressure fed bi-propellant using Mon25 and MMH
7	Hybrid using Mon25 and paraffin

Table 1. Configuration Descriptions shown in figure 1

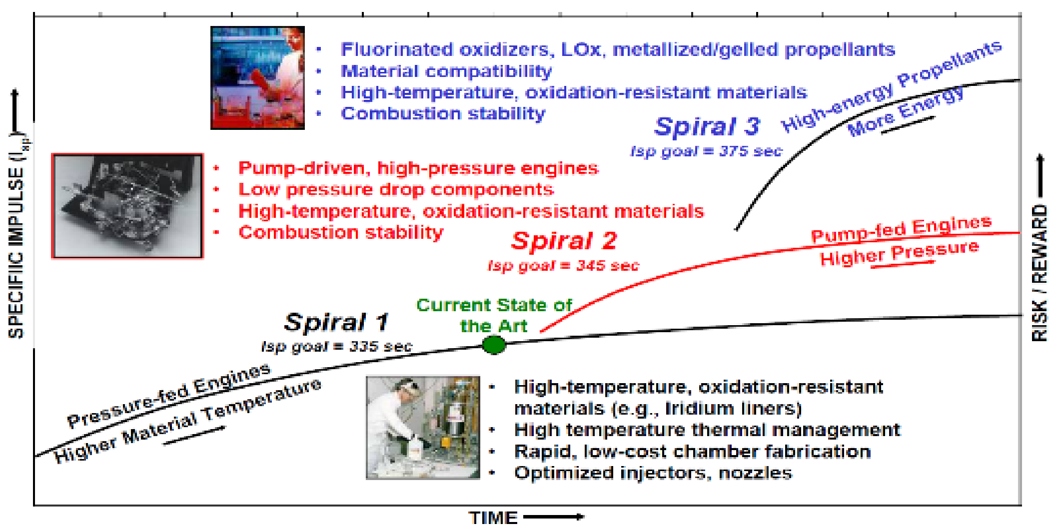

Figure 2. SOA performance for Storable Bi-propellant Engines.

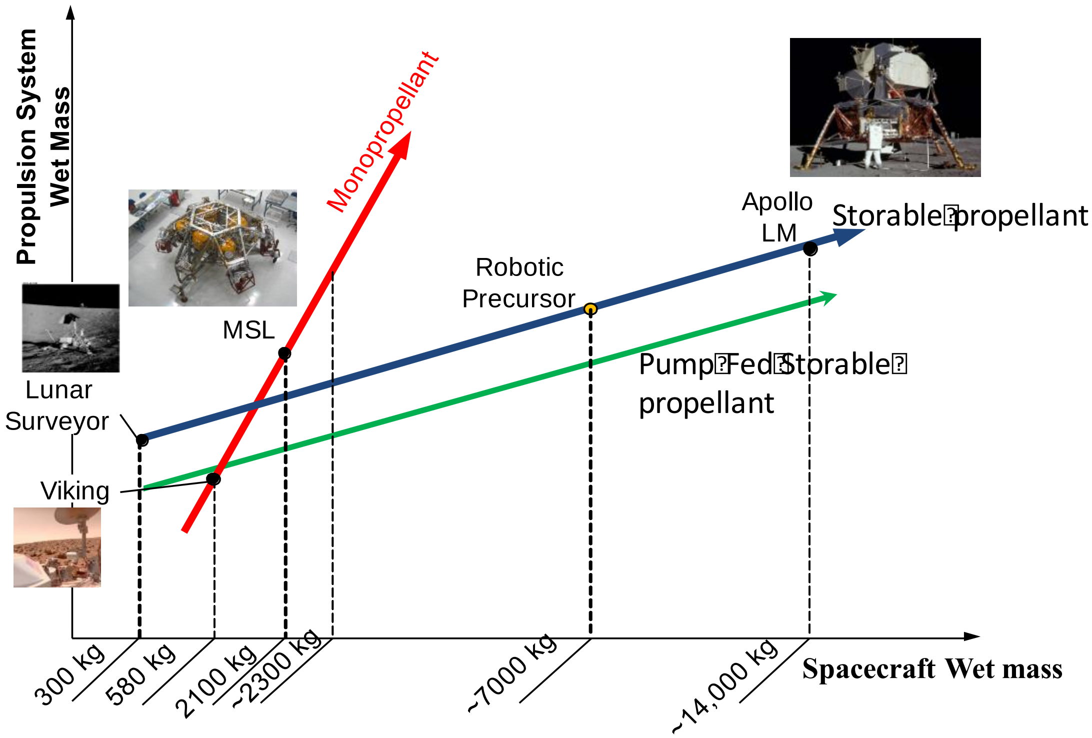

Figure 3. Historical perspective for Monopropellant and Bi-propellant propulsion systems

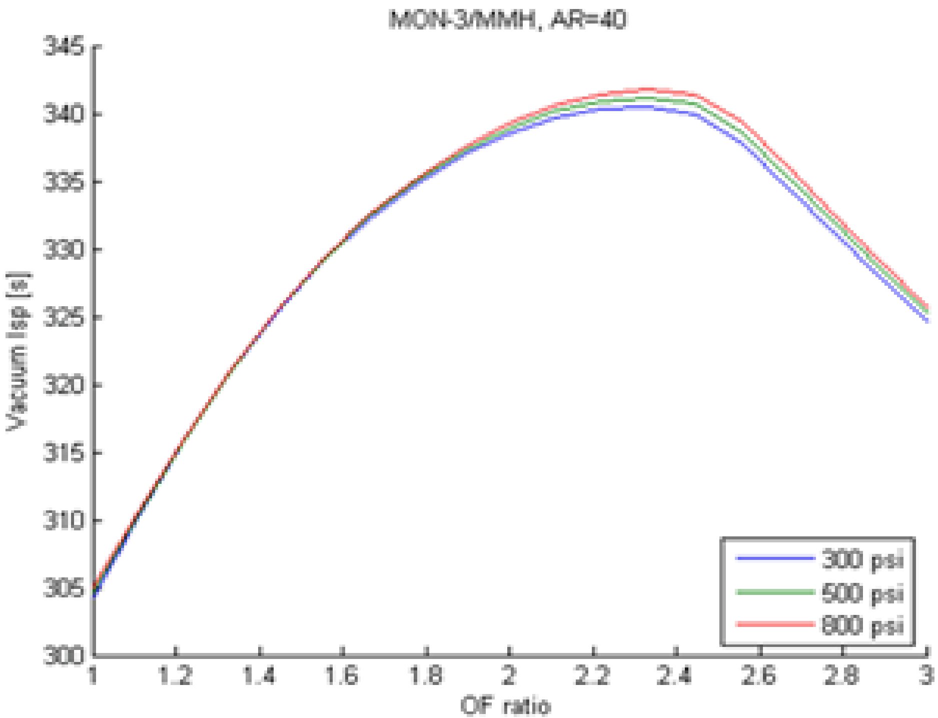

Figure 4 – Theoretical performance of MMH/NTO with mixture ratio and chamber pressure.

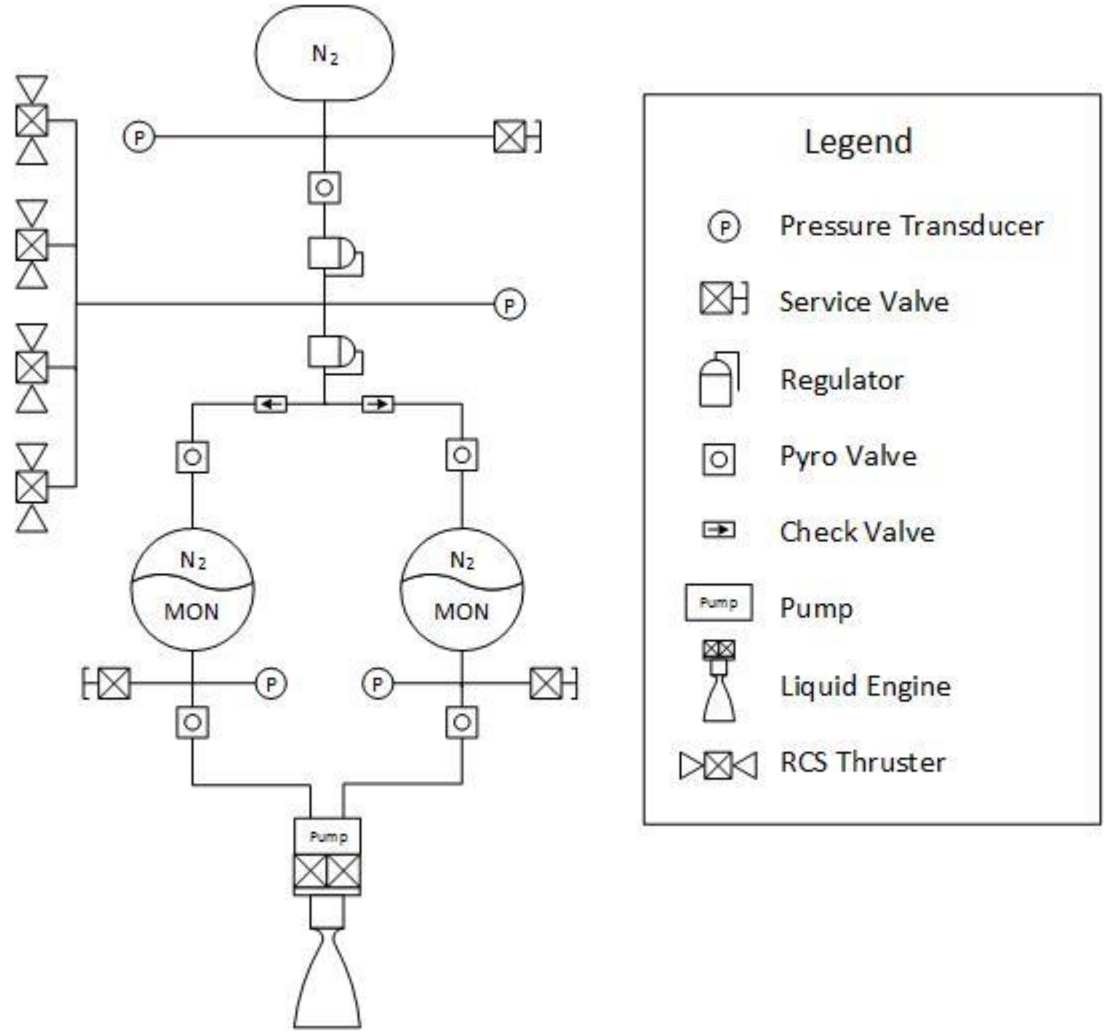

Figure 5. EDPF Potential component layout

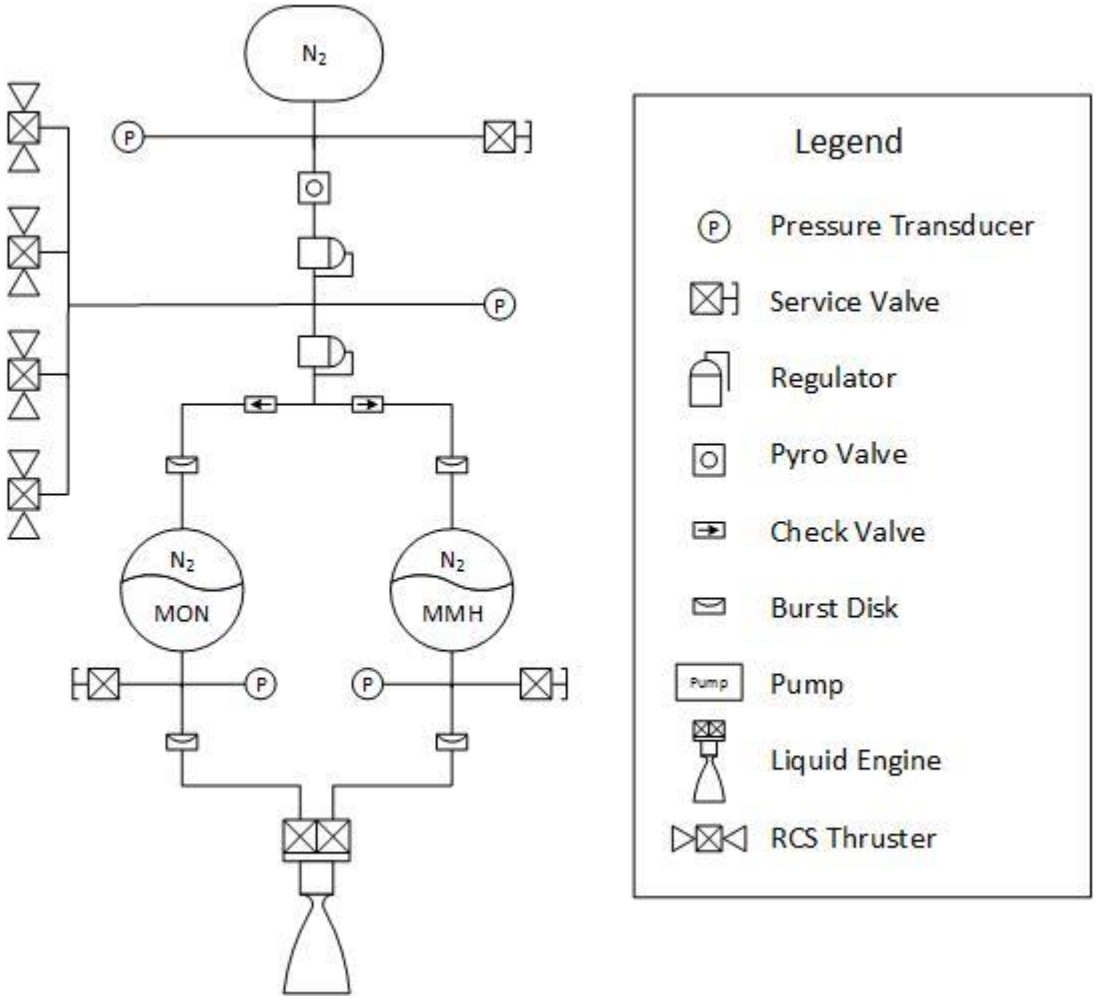

Figure 6. Potential MAV Pressure fed component layout

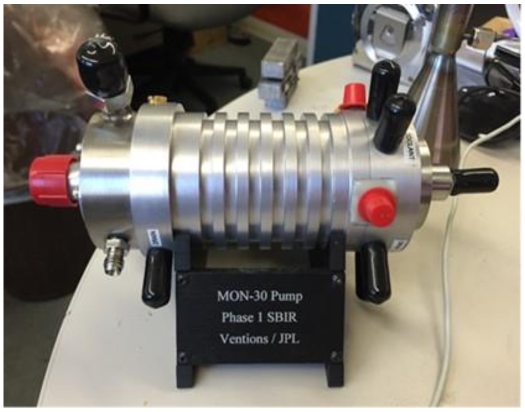

Figure 7. – Mon-30 EDPF

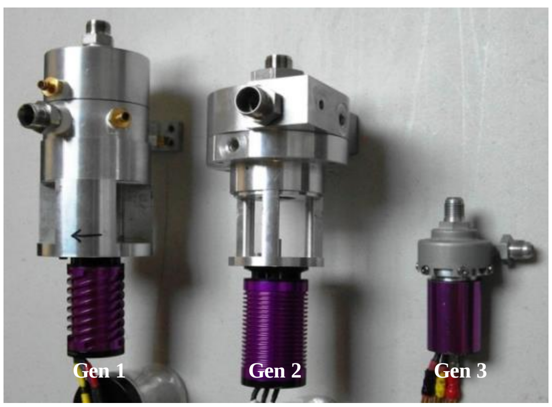

Figure 8. – Examples of Ventions LLC EDPF development

Component or Subsystem	**Regulated Biprop Total Mass (kg)**	**EDPF Biprop Total Mass (kg)**
Orbiting Sample	14.00	14.00
Avionics	3.78	3.78
Telecom	3.68	3.68
Structures	11.08	10.29
Mechanisms	0.29	0.29
Harness	3.69	3.44
Propellant & Pressurant Tanks	14.19	9.67
Main Engine Feed System	3.23	3.39
RCS system	3.25	2.02
Main Engine Assembly	11.36	13.81
Total Dry Mass	**68.55**	**64.37**

Table 2. - Mass properties for the two bi-propellant propulsion options

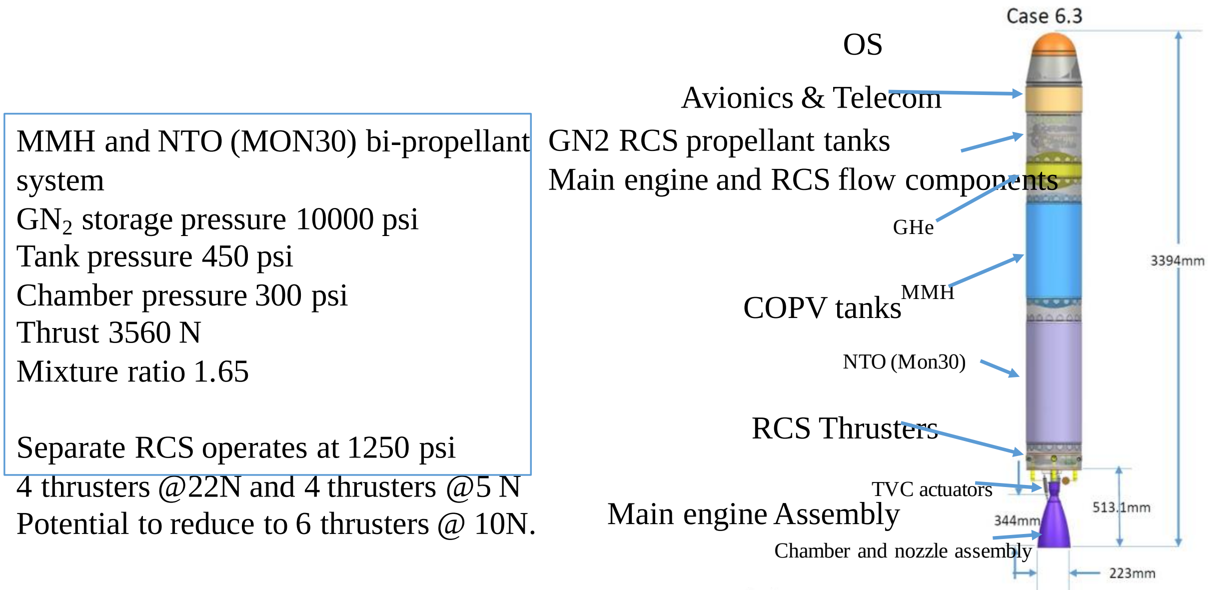

Figure 9. – Layout of EDPF bi-propellant propulsion system

Figure 10. – Layout of pressure fed bi-propellant propulsion system